PCT WORLD INTELLECTUAL PROPERTY ORGANIZATION
International Bureau

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 6 : H01M 10/46 — A1

(11) International Publication Number: WO 98/40925

(43) International Publication Date: 17 September 1998 (17.09.98)

(21) International Application Number: PCT/US98/04883

(22) International Filing Date: 12 March 1998 (12.03.98)

(30) Priority Data:

60/040,356	12 March 1997 (12.03.97)	US
60/051,049	27 June 1997 (27.06.97)	US

(81) Designated States: CA, CN, JP, European patent (AT, BE, CH, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).

Published
With international search report.
Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.

(71) Applicant: US NANOCORP. [US/US]; Suite 106, 20 Washington Avenue, North Haven, CT 06473–2342 (US).

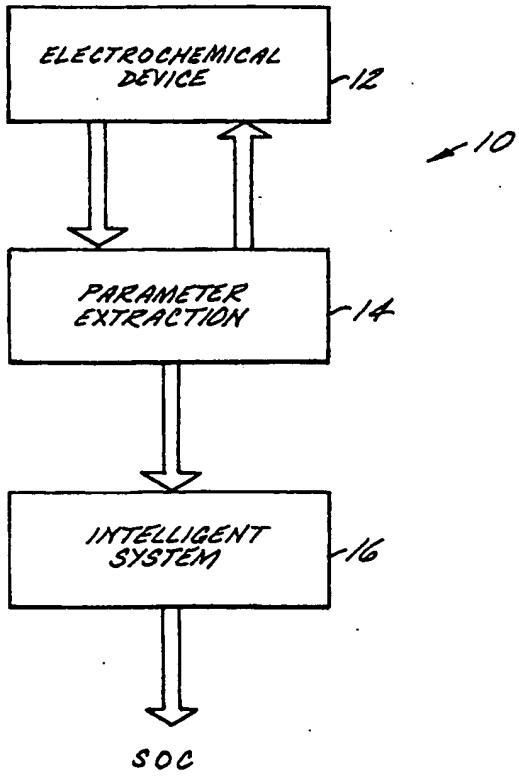
(72) Inventors: SINGH, Pritpal; 800 Lancaster Avenue, Villanova, PA 19085 (US). FENNIE, Craig, Jr.; 20 Washington Avenue, North Haven, CT 06473–2343 (US).

(74) Agent: COLBURN, Philmore, H., II; Fishman, Dionne, Cantor & Colburn, 88 Day Hill Road, Windsor, CT 06095 (US).

(54) Title: A METHOD FOR DETERMINING STATE–OF–CHARGE USING AN INTELLIGENT SYSTEM

(57) Abstract

A method for determining state of charge, SOC, of an electrochemical device (12) using fuzzy logic (i.e., an intelligent system) is presented. SOC of an electrochemical device is determined by an internal characteristic or parameter (or external operating and environmental conditions) (14) with an intelligent system (16). The electrochemical device (12) comprises such devices as primary ("throwaway") batteries, rechargeable batteries, fuel cells, a hybrid battery containing a fuel cell electrode and electrochemical supercapacitors. The intelligent system (16) is trained in the relationship between the characteristic of the electrochemical device and the SOC of the electrochemical device.



FOR THE PURPOSES OF INFORMATION ONLY

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AL	Albania	ES	Spain	LS	Lesotho	SI	Slovenia
AM	Armenia	FI	Finland	LT	Lithuania	SK	Slovakia
AT	Austria	FR	France	LU	Luxembourg	SN	Senegal
AU	Australia	GA	Gabon	LV	Latvia	SZ	Swaziland
AZ	Azerbaijan	GB	United Kingdom	MC	Monaco	TD	Chad
BA	Bosnia and Herzegovina	GE	Georgia	MD	Republic of Moldova	TG	Togo
BB	Barbados	GH	Ghana	MG	Madagascar	TJ	Tajikistan
BE	Belgium	GN	Guinea	MK	The former Yugoslav Republic of Macedonia	TM	Turkmenistan
BF	Burkina Faso	GR	Greece			TR	Turkey
BG	Bulgaria	HU	Hungary	ML	Mali	TT	Trinidad and Tobago
BJ	Benin	IE	Ireland	MN	Mongolia	UA	Ukraine
BR	Brazil	IL	Israel	MR	Mauritania	UG	Uganda
BY	Belarus	IS	Iceland	MW	Malawi	US	United States of America
CA	Canada	IT	Italy	MX	Mexico	UZ	Uzbekistan
CF	Central African Republic	JP	Japan	NE	Niger	VN	Viet Nam
CG	Congo	KE	Kenya	NL	Netherlands	YU	Yugoslavia
CH	Switzerland	KG	Kyrgyzstan	NO	Norway	ZW	Zimbabwe
CI	Côte d'Ivoire	KP	Democratic People's Republic of Korea	NZ	New Zealand		
CM	Cameroon			PL	Poland		
CN	China	KR	Republic of Korea	PT	Portugal		
CU	Cuba	KZ	Kazakstan	RO	Romania		
CZ	Czech Republic	LC	Saint Lucia	RU	Russian Federation		
DE	Germany	LI	Liechtenstein	SD	Sudan		
DK	Denmark	LK	Sri Lanka	SE	Sweden		
EE	Estonia	LR	Liberia	SG	Singapore		

A METHOD FOR DETERMINING STATE-OF-CHARGE USING AN INTELLIGENT SYSTEM

Background of the Invention:

The present invention relates to determining state of charge of an electrochemical device. More particularly, the present invention relates to determining state of charge of an electrochemical device using an intelligent system, e.g., a fuzzy logic system.

Presently there are three basic approaches to determining the state of charge (SOC) of batteries, Coulomb counting, response of a battery to an applied load, and batter impedance measurements.

The Coulomb counting approach involves the measurement of charge flow out of the battery into the load and charge flow from a battery charger to the battery. The Cumulative charge removed from the battery is used to estimate the battery's SOC with or without corrections being made for changes in battery capacity with discharge rate and battery temperature. The corrections to battery capacity made to compensate for battery temperature and discharge rate variations are performed using semi-empirical equations, such as the Peukert equation, as demonstrated by U.S. Patent No. 5,656,919. Other analytical equations used to adjust the battery SOC for discharge rate and battery temperature were reported by Alzieu et al in Journal of Power Sources 67 pp. 157 - 161

(1997). Another approach to coulomb counting is to use actual battery data stored in lookup tables to adjust for the battery SOC variation with discharge rate and battery temperature. A good example of this method is provided in U.S. Patent No. 5,372,898. Another example of this approach was presented by Freeman and Heacock in the High Frequency Power Conversion 1994 Conference Proceedings pp. 231- 241 (April 1994). These methods are commonly used in portable electronic applications but do not always work well in the case of variable loads. They are also not particularly accurate when interpolating between the data available in the lookup tables.

The response of a battery to a load can be used to determine battery SOC. By observing the voltage of the battery before, during, and after the application of a load, the battery response to the load may be used to determine the battery SOC. One example of this approach was presented by Peled in U.S. Patent No. 4,275,784. This patent describes a means of inferring the SOC of lithium batteries by using the battery temperature and the temporal voltage recovery profile of a battery after the removal of a fixed load on a battery, by comparison with reference tables for the given temperature and voltage recovery characteristics. A similar approach has been reported by Finger in U.S. Patent No. 4,460,870. These methods like the Coulomb counting methods above do not necessarily provide reliable interpolation between the conditions at which the batteries have been previously calibrated.

It is well known that the measurement of the internal impedance of a battery may be used to determine the battery's state of charge (SOC). U.S. Patent No. 3,562,634 describes a technique where the capacitances of nickel-cadmium batteries are used to determine the SOC of these batteries. This approach, however, is awkward to implement because it requires a standard reference curve to be used for comparing the measured capacitance in order to infer the battery's SOC.

Several patents, including U.S. Patent Nos. 4,678,998, 5,241,275, 5,650,937, and 5,369,364, and publications including Journal of Applied Electrochemistry, Blanchard, 22 pp. 1121-11128 (1992), Journal of Applied Electrochemistry, Viswanathan et al., 9 pp. 125-139 (1979), Journal of Applied Electrochemistry,

Karunithalaka et al., 13 pp. 577 - 586 (1983), and Doctoral Dissertation of John Weckesser, entitled An Evaluation of the Electrochemical Properties of Metal Hydride Alloys For Rechargeable Battery Applications, Rutger University (1993) describe different extraction techniques for determining the SOC of a battery having measured the complex internal impedance of the battery at various frequencies. These methods are cumbersome, computationally intensive, and difficult to automate. Also, battery-to-battery variation can be large enough that these techniques become unreliable.

Another approach to determining battery SOC from battery impedance measurements is described in U.S. Patent No. 3,984,762. This patent describes a means for measuring the phase angle of the complex impedance of a battery and a method for correlating this information with the battery's SOC. Although this method is relatively easy to implement, it is of limited value in that many batteries do not have a consistent correlation between the phase angle of their internal complex impedance and battery SOC.

U.S. Patent No. 4,743,855 describes an analytical method for determining battery SOC simply by measuring the battery's complex internal impedance at only two frequencies. This considerably simplifies the required electronic circuitry and required computation compared to having to measure the battery's complex internal impedance at many frequencies. Although, this analytical method may work reasonably well for some primary batteries, it is not well suited for rechargeable batteries.

U.S. Patent No. 5,132,626 a method is described whereby the internal impedance is measured at a single frequency and the battery SOC inferred from this measurement. The drawback of this approach, in general, is the difficulty in finding a single frequency at which the magnitude of the complex internal impedance of the battery correlates well with the battery's SOC.

Summary of the Invention:

The above-discussed and other drawbacks and deficiencies of the prior art are overcome or alleviated by the method for determining state of charge (SOC) of an

electrochemical device using an intelligent system, e.g., a fuzzy logic system, of the present invention. In accordance with the present invention, the state of charge of an electrochemical device is determined by an internal characteristic parameters (or external operating and environmental conditions) with an intelligent system. The electrochemical device comprises such devices as primary ("throwaway") batteries, rechargeable batteries, fuel cells, a hybrid battery containing a fuel cell electrode and electrochemical supercapacitors. The intelligent system is trained in the relationship between the characteristic and the related.

The intelligent system comprises any system that adaptively estimates or learns continuous functions from data without specifying how outputs depend on inputs. By way of example, the intelligent system includes an artificial neural system, a fuzzy system and other such model-free function estimators that learn. Learning, so-called, "tunes" an intelligent system. This learning process (also referred to as a training process) can be implemented in many ways. The intelligent system can be implemented using: an algorithm such as gradient descent and clustering used to tune neural networks and adaptive fuzzy systems; search optimization techniques such as those used by genetic algorithms; or an expert's guesses or trials and errors such as those used in fuzzy expert systems and fuzzy systems.

The above-discussed and other features and advantages of the present invention will be appreciated and understood by those skilled in the art from the following detailed description and drawings.

Brief Description of the Drawings:

Referring now to the drawings wherein like elements are numbered alike in the several FIGURES:

FIGURE 1 is a block diagram of a method for determining state of charge of an electrochemical device in accordance with the present invention;

FIGURE 2 is a block diagram of an additive fuzzy system for use in the intelligent system of the present invention;

FIGURE 3 is a block diagram of a method for determining state of charge of an electrochemical device in accordance with an embodiment of the present invention;

FIGURE 4A is a schematic diagram of a circuit for measuring battery impedance;

FIGURE 4B is a block diagram of an equivalent circuit model characteristic parameter extraction device of FIGURE 3;

FIGURE 4C is a plot of the log of the impedance versus battery cycle number;

FIGURE 5 is a plot of impedance function as a function of SOC versus Cycle #;

FIGURE 6 is a block diagram of an intelligent system for use in determining state of charge of the present invention;

FIGURE 7 is a block diagram of an additive fuzzy system for use in the intelligent system of the present invention;

FIGURES 8A-C are plots of membership functions for the fuzzy system of FIGURE 7;

FIGURE 9A is a circuit block diagram for determining battery impedance in accordance with the present invention;

FIGURE 9B is a circuit block diagram for determining state of charge in accordance with the present invention;

FIGURE 10 is a block diagram of a method for determining state of charge of an electrochemical device in accordance with another embodiment of the present invention;

FIGURE 11A is a circuit block diagram for sensing battery current in accordance with the present invention;

FIGURE 11B is a circuit block diagram for determining state of charge as a function of time with varying current and temperature;

FIGURE 11C is a circuit block diagram for determining state of charge in accordance with the present invention;

FIGURE 12 is a plot of discharge efficiency as a function of current and temperature;

FIGURE 13 is a block diagram of an additive fuzzy system for use in the intelligent system of the present invention;

FIGURES 14A and B are plots of membership functions for the fuzzy system of FIGURE 13; and

FIGURE 15 is a flowchart of the method for determining state of charge of an electrochemical device in accordance with the present invention.

Description of the Invention:

Referring to FIGURE 1, a system for determining State-of-Charge (SOC) in accordance with the present invention is generally shown at 10. System 10 comprises an electrochemical device 12 for which SOC is to be determined, a parameter extraction device 14 and an intelligent system 16. Electrochemical device 12 comprises such devices as primary ("throwaway") batteries, rechargeable batteries, fuel cells, a hybrid battery containing a fuel cell electrode and electrochemical supercapacitors. Intelligent system 16 is trained in the relationship between characteristic parameters of electrochemical device 12 and its SOC. These characteristic parameters are obtained by device 14 and provided to intelligent system 16 as inputs, with the SOC being the output of intelligent system 16.

Intelligent system 16 comprises any system that adaptively estimates or learns continuous functions from data without specifying how outputs depend on inputs, such as described in Neural Networks and Fuzzy System, by Bart Kosko, Prentice-Hall, 1992, which is incorporated herein by reference. By way of example, intelligent system 16 includes, but is not limited to, an artificial neural system, a fuzzy system and other such model-free function estimators that learn. Learning, so-called, "tunes" an intelligent system. The learning process (also referred to as a training process) can be implemented in many ways. Intelligent system 16 can be implemented using an algorithm such as gradient decent and clustering used to tune neural networks and adaptive fuzzy systems, such as described in Neural Networks and Fuzzy System, by Bart Kosko, Prentice-Hall, 1992. Intelligent system 16 can also be implemented using

search optimization techniques such as those used by genetic algorithms, see Genetic Algorithm and Fuzzy Logic System, Soft Computing Perspective (Advances in Fuzzy Systems - Applications and Theory, Vol. 7), by Elie Sanchez et al, World Scientific Pub. Co., 1997, which is incorporated herein by reference. Alternatively, intelligent system16 can be implemented by an expert's guesses or trials and errors such as those used in fuzzy expert systems and fuzzy systems, see Fuzzy Logic With Engineering Applications, by Timothy J. Ross, McGraw Hill, 1995, which is incorporated herein by reference. It will be appreciated that combinations of the above may also be employed, such as a fuzzy system/adaptive fuzzy system that uses gradient decent and/or clustering to develop an initial fuzzy system, then uses an expert 's knowledge to fine tune the system, see Fuzzy Engineering, by Bart Kosko, Prentice-Hall, 1997, which is incorporated herein by reference.

Referring to FIGURE 2, intelligent system 16 in a preferred embodiment comprises an additive fuzzy system 18 with centroid defuzzification 20. Additive fuzzy system 18, F, stores m fuzzy rules of the form, " If X is A_j then Y is B_j ", and computes the output $F(x)$ as the centroid of the summed and partially fired then-part fuzzy sets B'_j , see Fuzzy Engineering, by Bart Kosko, Prentice-Hall, 1997. Mathematically additive fuzzy system 18 is expressed by Equation 1 as:

$$F(x) = \frac{\sum_{j=1}^{m} w_j a_j(x) V_j c_j}{\sum_{j=1}^{m} w_j a_j(x) V_j}$$

EQUATION 1

$$a_j(x) = \prod_{i=1}^{n} a_j^i(x_i)$$

EQUATION 2

$$B = \sum_{j=1}^{m} w_j B'_j = \sum_{j=1}^{m} w_j a_j(x) B_j$$

EQUATION 3

where:

w_j is a weight of rule j,

a_j^i represents if-part set function (membership function of input i of rule j on input i),

a_j represents joint if-part set function (result of "a_j^1 'and' a_j^2 ..... 'and' a_j^i) that states the degree to which the input x belongs to the if-part fuzzy set a_j,

B_j represents then-part set function (membership function j on the output),

V_j is the finite positive volume (or area) of the then-part set B_j,

c_j is the centroid of the then-part set B_j,

B_j - scaled then-part set (scaled output membership function j, result of $a_j(x)B_j$), and

B - output set prior to defuzzification.

In linguistic terms, additive fuzzy system 18 can be described in terms of a set of if-then rules:

RULE 1: If X_1 is $a^1{}_1$ and X_2 is $a^2{}_1$ .... and X_n is $a^n{}_1$, then $F(X)$ is B_1 ,

RULE 2: If X_1 is $a^1{}_2$ and X_2 is $a^2{}_2$ .... and X_n is $a^n{}_2$, then $F(X)$ is B_2 ,

RULE m: If X_1 is $a^1{}_m$ and X_2 is $a^2{}_m$ .... and X_n is $a^n{}_m$, then $F(X)$ is B_m ,

where m is the number of rules and n is the number of inputs.

The linguistic description and the mathematical description of additive fuzzy system 18 are equivalent. They are merely different views of the same fuzzy system. Both approaches map a given input X to a given output F(X) by a process known as fuzzy inference. The following example demonstrates the fuzzy inference process. First, fuzzify the inputs by taking the inputs and determine the degree to which they belong to each of the appropriate input fuzzy sets via membership functions. Mathematically expressed as: "$a_1^1(X_1)$, $a_1^2(X_2)$, ...,$a_1^m(X_m)$ ". Linguistically expressed

as: "If $X_1 = a_1^1$, If $X_2 = a_1^2$, ..., If $X_m = a_1^m$". Second, apply a fuzzy operator by combining if-part sets of a given rule to obtain one number that represents the result of the antecedent for that rule. Mathematically expressed as EQUATION 2 hereinabove. Linguistically expressed as: "a_1^1 'and' a_1^2 'and' a_1^m " where 'and' is the T-norm product. Third, apply an implication method by shaping the consequent (or output fuzzy set) based on the result of the antecedent for that rule. Mathematically expressed as: "$B_1 = a_1(X)B_1$ ". Linguistically expressed as: "If $a_1(X)$,then B_1". Fourth, aggregate all outputs by combining the consequent of each rule to form one output fuzzy set. Mathematically expressed as EQUATION 3 hereinabove. Fifth, defuzzify by mapping the output fuzzy set to a crisp number. Mathematically expressed as "F(x) =centroid(B) = EQUATION 1". In general see Fuzzy Logic Toolbox, for use with MATLAB, The Mathworks, Inc. by Jang and Gulley.

By way of example, a supervised gradient descent, can learn or tune additive fuzzy system 18 given by EQUATION 1 by changing the rule weights w_j, the then-part volumes V_j, the then-part centroids c_j, or the if-part set functions a_j.

Referring to FIGURE 3, system 10 determines the SOC of a battery 12 by relating the internal electrical characteristics of a battery to its SOC. In the preferred embodiment the internal electrical characteristic parameter extraction device comprises an impedance measuring device 20. System 10 comprises battery 12 for which the SOC is to be determined, an impedance measuring device 20, a preprocessor and intelligent system 16. In the preferred embodiment the preprocessor comprises an equivalent circuit parameter extraction device and a battery cycle device.

Referring to FIGURE 4A, a circuit 24 for measuring battery impedance is shown. Circuit 24 comprises battery 12 whose impedance is to be measured, an a.c. voltage generator 26 of variable frequency, and a d.c. variable voltage generator 28. Battery 12 and generators 26 and 28 are connected in series in any order but in such a way that battery 12 and the d.c. generator 28 have in common poles of the same sign, in this example the positive poles. The no-load voltage of battery 12 is designated as E_0,

the effective voltage of a.c. generator 26 is designated as V and the voltage of d.c. generator 28 is designated as E. Voltage E is chosen so as to be equal to E_0 to prevent battery 12 issuing a direct current. In this way, the current flowing in the loop made up of battery 12 and generators 26 and 28 has no direct component and its alternating component designated I is determined by the voltage V. Variables V and I are complex numbers and their ratio V/I = Z = Z' + jZ" defines the internal complex impedance of battery 12. This impedance has a real or resistive part Z' and an imaginary or reactive part Z". The magnitude of this impedance, |Z|, is given by $|Z| = (Z'^2 + Z"^2)^{1/2}$. The battery impedance is a function of the frequency f of the a.c. voltage. In some cases, the battery impedance at a particular frequency also changes with the battery's cycle number. A fully charged battery that is discharged and then recharged to its original state is said to have gone through a complete battery cycle. A battery's cycle number is the cumulative number of cycles that the battery has gone through.

Referring now to FIGURE 4B, equivalent circuit model characteristic parameters extraction device 14 is shown for extracting electrical parameters from the impedance data (i.e., $Z(f_{.4HZ})$, $Z(f_{1000HZ})$). It has been determined that in the case of nickel metal hydride batteries, the battery impedance measured at a frequency of 1000 Hz correlates well with the battery cycle number above about 100 cycles, seeDoctoral Dissertation of John Weckesser, entitled An Evaluation of the Electrochemical Properties of Metal Hydride Alloys For Rechargeable Battery Applications, Rutger University (1993), which is incorporated herein by reference.

Referring to FIGURE 4C, variation of the logarithm of the impedance (log Z) with battery cycle number for a nickel metal hydride battery is shown. This data allows determination of the battery cycle number (independently of battery state of charge) above about 100 cycles. Further, series capacitance of nickel metal hydride batteries varies with both cycle number and battery state of charge. Also, the values of the series capacitance of the nickel metal hydride batteries can be determined by measuring the internal impedance of the batteries at many frequencies and using a circuit model with

different circuit elements to fit the complete impedance spectrum., again see Doctoral Dissertation of John Weckesser, Rutger University (1993).

In accordance with the present invention, an effective series capacitance value can be determined by a simple analysis of the battery impedance measured at two frequencies. The effective series capacitance is obtained by measuring the impedance of the battery at 0.4 Hz and measuring the impedance at 1000 Hz. The effective series capacitance is given by the expression $C_{eff} = 1/(Z(f_{.4Hz}) - 1.12\ Z(f_{1000Hz}))$. A plot of this function is shown in FIGURE 5, wherein a similar functional relationship to the battery cycle number and battery state of charge is found. This is used by system 10' to determine battery 12 state of charge (SOC) given battery 12 impedance measurements made at 0.4 Hz and 1000 Hz.

Referring to FIGURE 6, intelligent system 16 is trained in the relationship between equivalent circuit model internal electrical characteristic parameters and the SOC of the battery, whereby the intelligent system 16 learns the underlying function f that relates C_{eff} and Cycle $\#(f_{rc}(R_{ohm}))$ to SOC.

Referring to FIGURE 7, additive fuzzy system 18 learns the relationship between input variables, C_{eff} and Cycle # , and output variables, battery SOC, by use of an expert knowledge and trials and errors. It will be appreciated that any learning method previously discussed can be used to tune the fuzzy system. Also that any intelligent system previously mentioned can be employed in place of the additive fuzzy system. Input membership functions for the fuzzy system are shown in FIGURES 8A and B and the output membership functions are shown in FIGURE 8C. There are four membership functions for the cycle #, four membership functions for the effective series capacitance C_{eff}, and four membership functions for the SOC of battery 12. The following rules are applied:

Rule 1. If (Cycle _Number is Low) and (Capacitance is Low) then (State_of_Charge is Very Low) (1)

Rule 2. If (Cycle _Number is Low) and (Capacitance is Medium) then (State_of_Charge is Low) (1)

Rule 3. If (Cycle _Number is Low) and (Capacitance is High) then (State of Charge is High) (1)

Rule 4. If (Cycle _Number is Low) and (Capacitance is Very_High) then (State_of_Charge is High) (1)

Rule 5. If (Cycle Number is medium) and (Capacitance is Low) then (State_of_Charge is Very Low)(1)

Rule 6. If (Cycle Number is medium) and (Capacitance is medium) then (State_of_Charge is Low) (1)

Rule 7. If (Cycle_Number is medium) and (Capacitance is High) then (State_of_Charge is medium) (1)

Rule 8. If (Cycle_Number is medium) and (Capacitance is Very_High) then (State_of_Charge is High) (1)

Rule 9. If (Cycle Number is high) and (Capacitance is Low) then (State_of_Charge is Very_Low)

Rule 10. If (Cycle_Number is high) and (Capacitance is medium) then (State_of_Charge is medium) (1)

Rule 11. If (Cycle_Number is high) and (Capacitance is High) then (State_of_Charge is High) (1)

Rule 12. If (Cycle_Number is high) and (Capacitance is Very_High) then (State_of_Charge is High) (1)

Rule 13. If (Cycle_Number is very high) and (Capacitance is Low) then (State_of_Charge is Low)(1)

Rule 14. If (Cycle_Number is very_high) and (Capacitance is medium) then (State_of_Charge is High)

Rule 15. If (Cycle Number is very high) and (Capacitance is High) then (State_of_Charge is High) (1)

It will be appreciated that the SOC of battery 12 is really a function of the complex impedance and that the parameters, C_{eff} and R_{ohm}, are useful in developing a

circuit model of battery 12. The direct relationship between the complex impedance and SOC follows:

$$SOC = f(C_{eff}, \text{Cycle \#}) \qquad \text{EQUATION 4,}$$

$$C_{eff} = f(Z(f_{.4}), Z(f_{1000})) = \frac{1}{Z(f_{.4}) - 1.12Z(f_{1000})} \qquad \text{EQUATION 5,}$$

$$\text{Cycle \#} = f_{rc}(R_{ohm}) = f_{rc}(f(Z(f_{1000}))) = f_{rc}(Z(f_{1000})) \qquad \text{EQUATION 6,}$$

therefore,

$$SOC = f(Z(f_{.4}), Z(f_{1000})) \qquad \text{EQUATION 7.}$$

Intelligent system 16 may be trained directly in the relationship between the impedance, $Z_{.4Hz}$ and Z_{1000Hz}, and SOC. It will be appreciated that the present embodiment is not dependent upon the impedance at the particular frequencies, .4 Hz and 1000 Hz, such being merely exemplary.

Referring to FIGURE 9A, a circuit 30 for measuring impedance of battery 12 at two frequencies is generally shown. Circuit 30 comprises battery 12 whose impedance is to be measured and an a.c. signal generator 32. A small amplitude, perturbing sinusoidal signal, $x(t)= X_0 \sin(\omega t)$, is applied to battery 12. The response of battery 12 to this perturbing signal is $S(t) = X_0 K(\omega)\sin(\omega[t + \phi(\omega)])$ and is correlated with two reference signals, one in phase with x(t) and the other 90° out of phase with x(t), i.e., $\sin(t\omega)$ and $\cos(\omega t)$, in order to calculate :

$$\Re - \frac{1}{T}\int_0^T S(t)\sin\omega t dt$$

EQUATION 8

$$\Im - \frac{1}{T}\int_0^T S(t)\cos\omega t dt$$

EQUATION 9

This allows the elimination of higher order harmonics than the fundamental and with an appropriate selection of a frequency window and multiple measurements, noise rejection can be very high. In the limit as

$$T \rightarrow \infty, \Re \rightarrow K(\omega)\cos\phi(\omega), \Im \rightarrow K(\omega)\sin\phi(\omega)$$

where K(ω) represents the amplitude of the impedance at frequency ω/2π and φ(ω) represents the phase of the impedance at frequency ω/2π. Circuit 30 allows the determination of the impedance at different frequencies and may be set up to measure the impedance at the two frequencies of interest, such an instrument which can be used to perform the impedance measurements is commercially available as the Solartron 1260 Impedance/Gain-Phase Analyzer.

To determine battery SOC once the impedance is known, a circuit 34 (FIGURE 9B) may be used. The impedance values at the two frequencies from circuit 30 are fed into a microcontroller 34 (e.g., Motorola MC68HC11/12) either as analog or digital signals, analog signals would be fed into the A/D converters on microcontroller 34 where they would be converted to digital signals. The impedance at 1000 Hz., Z_1, is stored in a first memory location and the impedance at 0.4 Hz., Z_2, is stored at a second memory location. The impedance Z_2 is then multiplied by a factor of, e.g., 1.12 in microcontroller 34 and the result stored in a third memory location. The difference between Z_1 and $1.12xZ_2$ is then calculated in microcontroller 34 and the difference stored in a fourth memory location. The inverse of this quantity located in the fourth memory location is then calculated and the result stored in a fifth memory location. The impedance at 1000 Hz stored in the first memory location and the impedance stored in the fifth memory location serve as the input variables for the fuzzy system to determine battery 12 state of charge, as described above. The battery state of charge is then output to a display driver 36 and interfaced to a liquid crystal display 38.

Referring to FIGURE 10, an alternative system for determining the SOC of battery 12 by relating the external operating conditions such as, e.g., discharge rate, cycle number, calendar life and recovery time to a specified open circuit voltage (OCV)

after a deep discharge and environmental conditions such as, e.g., temperature, battery orientation, magnetic field and g-force, and which infer the discharge efficiency to its discharge efficiency, then adjusting the theoretical capacity accordingly is generally shown at 40. System 40 comprises battery system 12 for which SOC is to be determined, an operating characteristic processing unit 42 (for determining, e.g., discharge rate, D_{Rate}, and coulombs withdrawn from the battery, C_W) an environmental characteristic processing unit 44 (for determining, e.g., battery temperature T_{batt}), intelligent system 16 (for determining discharge efficiency, D_{isseff}) and a processing unit 46 for determining SOC.

In this embodiment, intelligent system 16 is trained in the relationship between the external operating conditions and environmental conditions and the discharge efficiency, to compute battery discharge efficiency based on measurements of the current flow out of the battery, and the temperature of the battery. Referring to FIGURE 11A, a circuit 50 for sensing battery current comprises a current sensor 52 which is connected in series between battery 12 and a load 54. The current to load 54 is measured in either direction , i.e., from load 54 to battery 12 or from battery 12 to load 54. Current sensor 52 may be a shunt resistor across which a voltage drop is measured, the magnitude and sign of the voltage drop being indicative of the magnitude and direction of the current flow. A temperature sensor 56 is attached to battery 12 so that it is in intimate thermal contact with battery 12.

Referring to FIGURE 12, discharge efficiency curves for primary Li/SO_2 batteries as a function of current (discharge rate) and temperature are shown. The discharge efficiency of the battery is a measure of the battery's capacity and varies with the battery's current and temperature. The discharge efficiency curves may be used to compensate for the available capacity for a battery depending on discharge rate and temperature conditions.

To determine the battery SOC as a function of time with varying current and temperature a circuit 60 (FIGURE 11B) may be used. Circuit 60 comprises current sensor 50 which provides current information for use by processing unit 46 and is

integrated over time in a current integrator 62 yielding the total charge consumed. When a total charge of one coulomb has been accumulated in current integrator 62, this charge is modified by the discharge efficiency and subtracted from the total charge previously stored. The modification of the charge is performed by simply dividing the one coulomb count by the discharge efficiency, in processing unit 46 (see U.S. Patent No. 5,372,898 to Atwater which is incorporated herein by reference). Additionally, processing unit 46 determines the discharge efficiency during the one coulomb discharge cycle using fuzzy logic as described below. The fuzzy logic process for determining the discharge efficiency of the battery is also performed in processing unit 46. The calculation for reducing the stored available charge by the modified one coulomb charge (modified by the discharge efficiency of battery 12 during this particular discharge period) is also performed in processing unit 46. The available charge in the battery is the previous stored charge, which in the case of a fully charged battery is the nominal rated capacity, minus the charge removed from the battery which is the one coulomb charge modified by the discharge efficiency. The available charge is displayed on a battery state of charge indicator 64.

Referring to FIGURE 13, a generalized additive fuzzy system, know as Sugeno Inference system (see Fuzzy Logic Toolbox, for use with MATLAB, The Mathworks, Inc. by Jang and Gulley also see, Lee, C.C., Fuzzy Logic In Control Systems: Fuzzy Controller - 1 and 2, IEEE Transactions on Systems, Man and Cybernetics, Vol. 20, No. 2, p. 404 - 435, 1990) is generally shown, which learns the relationship between the input variables, discharge rate and battery temperature, and output variable, discharge efficiency. The subtractive clustering algorithm is used to develop the input membership functions, and the rules. The subtractive clustering algorithm determines where five clusters in the three-dimensional data (two inputs and one output) with each cluster representing a rule. The projection of each cluster onto each input space determines the position of each input membership function. Accordingly, there are five membership functions for both discharge rate and temperature. These membership functions (FIGURES 14A and B), some of these membership functions overlap.

Therefore, there are three distant membership functions for discharge rate and two for temperature. Finally, a linear least squares method is used to determine coefficients of the output membership functions, further description of the subtractive clustering algorithm and the least squares method is found in Fuzzy Logic Toolbox, for use with MATLAB, The Mathworks, Inc. by Jang and Gulley.

Referring to FIGURE 11C, current from battery 12 to load 54 is sensed by a sensed resistor 52. A temperature sensor 56 (e.g., LM35) is used to measure the temperature of the battery case. These two analog signals are fed into analog-to-digital converters (A/D) 66 and 68 inputs to microcontroller 46. It will be noted that a Motorola 68HC12 microcontroller has the advantages of having fuzzy logic instructions built into the instruction set of the microcontroller.

The fuzzy logic model is used to determine discharge efficiency. Current integration is used to count charge up to a count of one coulomb. SOC is then computed by modifying the one coulomb counted charge by the discharge efficiency and subtracting this either from the nominal capacity (for the first calculation) or from the previous SOC for subsequent calculations. Current integration is performed digitally in microcontroller 46 using the sensed current and the counter on microcontroller 46. Digital SOC data is then transferred to a liquid crystal display driver 70 (e.g., AY0438) and on to the liquid crystal display 72. This display may be in the form of a bar graph or in the form of a 3 1/2 digit character display.

FIGURE 15 shows a flowchart of the logical basis for the battery SOC determination. This program is initiated a block 70 then the initial battery capacity is read at block 72. Battery current is read into an accumulator A at block 74. A counter is then started at block 76 to provide a count (block 78). The count is monitored and when it reaches 1ms the program continues (block 80). Then battery current is multiplied by time at block 82. This is then added to the previous Coulomb count at block 84. If Coulomb count is 1C then the program continues (block 86), otherwise return to block 74. The discharge efficiency is calculated within a subroutine at block 88. The SOC is then determined at block 90 and sent to a display driver at block 92. If

the SOC is zero (block 94) the program terminates (block 96), otherwise return to block 74.

Existing software microcontroller development tools are available for implementing the above steps, e.g., the software development tools for the Motorola 68HC11 microcontroller . These tools can be used to implement the software for taking the current measurements and for calculating battery SOC. To implement the fuzzy logic algorithm to determine the discharge efficiency of the primary Li/SO_2 cell, the software TILShell can be used together with the 68HC11 assembler program. For implementation of the code on the Motorola 68HC12 microcontroller, manual coding is required of the model developed using the fuzzy logic toolbox for MATLAB using the fuzzy logic instructions for the 68HC12. Alternatively, the FuzzyTECH software from Inform Software Corp. can be used to implement the fuzzy logic algorithm since this software already has the drivers to program the 68HC12 microcontroller.

While preferred embodiments have been shown and described, various modifications and substitutions may be made thereto without departing from the spirit and scope of the invention. Accordingly, it is to be understood that the present invention has been described by way of illustrations and not limitation.

What is claimed is:

CLAIM 1. A method of determining a state of charge of an electrochemical device, comprising:

detecting at least one characteristic of said electrochemical device; and

determining said state of charge of said electrochemical device from an intelligent system trained in a relationship between said at least one characteristic and said state of charge.

CLAIM 2. The method of determining said state of charge of claim 1 wherein said at least one characteristic comprises at least one internal electrical characteristic.

CLAIM 3. The method of determining said state of charge of claim 1 wherein said at least one characteristic comprises at least one external characteristic.

CLAIM 4. The method of determining said state of charge of claim 2 wherein said at least one internal electrical characteristic comprises at least one internal impedance of said electrochemical device.

CLAIM 5. The method of determining said state of charge of claim 4 wherein said at least one internal impedance comprises a first internal impedance at a first frequency.

CLAIM 6. The method of determining said state of charge of claim 5 wherein said at least one internal impedance further comprises a second internal impedance at a second frequency.

CLAIM 7. The method of determining said state of charge of claim 1 wherein said intelligent system comprises a fuzzy system.

CLAIM 8. The method of determining said state of charge of claim 7 wherein said fuzzy system comprises an additive fuzzy system.

CLAIM 9. The method of determining said state of charge of claim 8 wherein said additive fuzzy system mathematically comprises:

$$F(x) = \frac{\sum_{j=1}^{m} w_j a_j(x) V_j c_j}{\sum_{j=1}^{m} w_j a_j(x) V_j}$$

$$a_j(x) = \prod_{i=1}^{n} a_j^i(x_i)$$

$$B = \sum_{j=1}^{m} w_j B_j' = \sum_{j=1}^{m} w_j a_j(x) B_j$$

where,

w_j is a weight of rule j,

a_j^i represents if-part set function, membership function of input i of rule j on input i,

a_j represents joint if-part set function, result of "a_j^1 'and' a_j^2 ..... 'and' a_j^i, that states a degree to which an input x belongs to the if-part fuzzy set a_j,

B_j represents then-part set function, membership function j on an output,

V_j is a finite positive volume or area of the then-part set B_j,

c_j is a centroid of the then-part set B_j,

B_j' is a scaled then-part set, scaled output membership function j, result of $a_j(x)B_j$, and

B is an output set prior to defuzzification.

CLAIM 10. The method of determining said state of charge of claim 4 wherein said at least one internal impedance includes a resistive part and a reactive part.

CLAIM 11. The method of determining said state of charge of claim 1 wherein said electrochemical device comprises a primary battery, a rechargeable battery, a fuel cell, a hybrid battery containing a fuel cell electrode or an electrochemical supercapacitor.

CLAIM 12. The method of determining said state of charge of claim 3 wherein said at least one external characteristic comprises an external operating condition and an environmental condition.

CLAIM 13. The method of determining said state of charge of claim 12 wherein said relationship between said at least on external characteristic and said state of charge includes:

a relationship between said external operating condition and said environmental condition and a discharge efficiency of said electrochemical device.

CLAIM 14. The method of determining said state of charge of claim 13 wherein said external operating condition comprises current flow from said electrochemical device and said environmental condition comprises temperature of said electrochemical device.

CLAIM 15. The method of determining said state of charge of claim 13 wherein said relationship between said at least on external characteristic and said state of charge further includes:

a relationship between said discharge efficiency and said state of charge.

CLAIM 16. The method of determining said state of charge of claim 8 wherein said additive fuzzy system includes a subtractive clustering algorithm for developing input membership functions and rules.

CLAIM 17. A system for determining a state of charge of an electrochemical device, comprising:

a sensor for detecting at least one characteristic of said electrochemical device and providing a sensed signal indicative thereof; and

a signal processor responsive to said sensed signal for determining said state of charge of said electrochemical device and providing a state of charge signal, said signal processor including an intelligent system trained in a relationship between said at least one characteristic and said state of charge.

CLAIM 18. The system for determining said state of charge of claim 17 wherein said at least one characteristic comprises at least one internal electrical characteristic.

CLAIM 19. The system for determining said state of charge of claim 17 wherein said at least one characteristic comprises at least one external characteristic.

CLAIM 20. The system for determining said state of charge of claim 18 wherein said at least one internal electrical characteristic comprises at least one internal impedance of said electrochemical device.

CLAIM 21. The system for determining said state of charge of claim 20 wherein said at least one internal impedance comprises a first internal impedance at a first frequency.

CLAIM 22. The system for determining said state of charge of claim 21 wherein said at least one internal impedance further comprises a second internal impedance at a second frequency.

CLAIM 23. The system for determining said state of charge of claim 17 wherein said intelligent system comprises a fuzzy system.

CLAIM 24. The system for determining said state of charge of claim 23 wherein said fuzzy system comprises an additive fuzzy system.

CLAIM 25. The system for determining said state of charge of claim 24 wherein said additive fuzzy system mathematically comprises:

$$F(x) = \frac{\sum_{j=1}^{m} w_j a_j(x) V_j c_j}{\sum_{j=1}^{m} w_j a_j(x) V_j}$$

$$a_j(x) = \prod_{i=1}^{n} a_j^i(x_i)$$

$$B = \sum_{j=1}^{m} w_j B_j' = \sum_{j=1}^{m} w_j a_j(x) B_j$$

where,

w_j is a weight of rule j,

a_j^i represents if-part set function, membership function of input i of rule j on input i,

a_j represents joint if-part set function, result of "a_j^1 'and' a_j^2 ..... 'and' a_j^i, that states a degree to which an input x belongs to the if-part fuzzy set a_j,

B_j represents then-part set function, membership function j on an output,

V_j is a finite positive volume or area of the then-part set B_j,

c_j is a centroid of the then-part set B_j,

B_j' is a scaled then-part set, scaled output membership function j, result of $a_j(x)B_j$, and

B is an output set prior to defuzzification.

CLAIM 26. The system for determining said state of charge of claim 20 wherein said at least one internal impedance includes a resistive part and a reactive part.

CLAIM 27. The system for determining said state of charge of claim 17 wherein said electrochemical device comprises a primary battery, a rechargeable battery, a fuel cell, a hybrid battery containing a fuel cell electrode or an electrochemical supercapacitor.

CLAIM 28. The system for determining said state of charge of claim 19 wherein said at least one external characteristic comprises an external operating condition and an environmental condition.

CLAIM 29. The system for determining said state of charge of claim 28 wherein said relationship between said at least on external characteristic and said state of charge includes:

a relationship between said external operating condition and said environmental condition and a discharge efficiency of said electrochemical device.

CLAIM 30. The system for determining said state of charge of claim 29 wherein said external operating condition comprises current flow from said electrochemical device and said environmental condition comprises temperature of said electrochemical device.

CLAIM 31. The system for determining said state of charge of claim 29 wherein said relationship between said at least on external characteristic and said state of charge further includes:

a relationship between said discharge efficiency and said state of charge.

CLAIM 32. The system for determining said state of charge of claim 24 wherein said additive fuzzy system includes a subtractive clustering algorithm for developing input membership functions and rules.

CLAIM 33. The system for determining said state of charge of claim 17 further comprising:

a display responsive to said state of charge signal for displaying said state of charge.

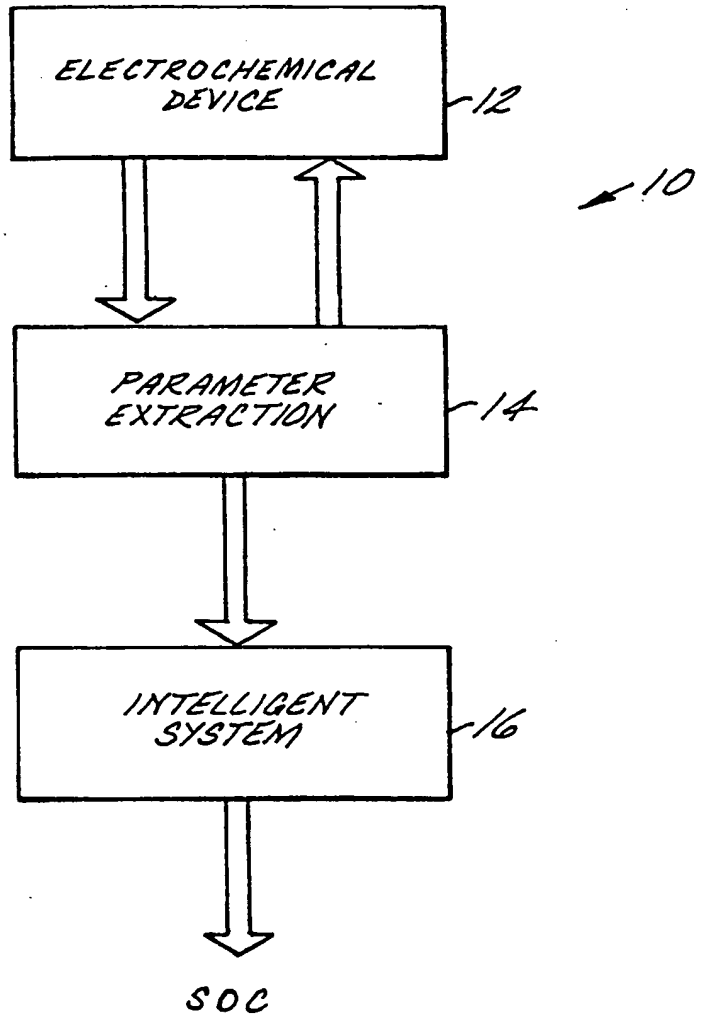

ELECTROCHEMICAL DEVICE
12
10
PARAMETER EXTRACTION
14
INTELLIGENT SYSTEM
16
SOC

FIG. 1

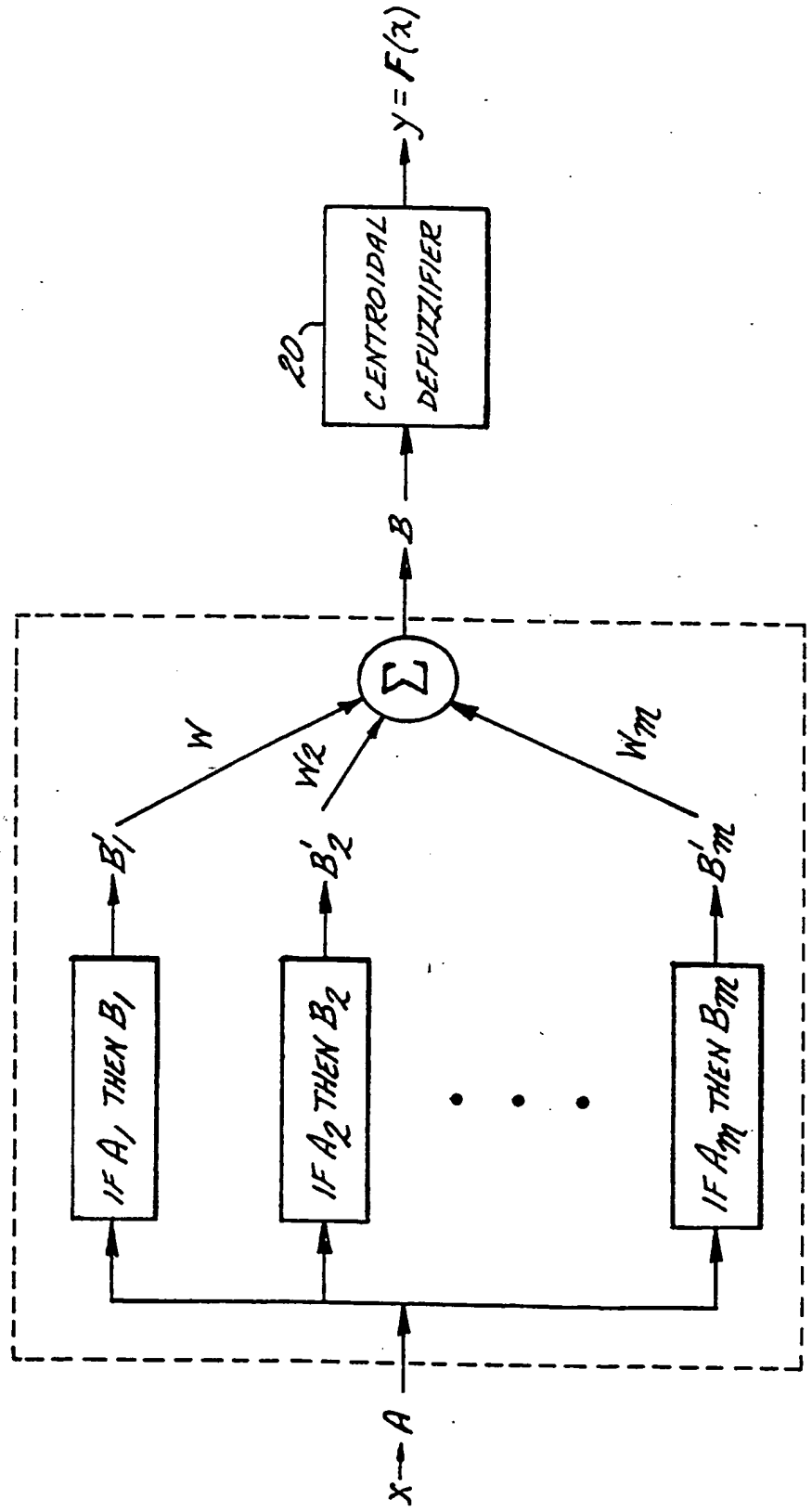

y = F(x)
20
CENTROIDAL DEFUZZIFIER
B
Σ
W
W2
Wm
B'1
B'2
B'm
IF A1 THEN B1
IF A2 THEN B2
IF Am THEN Bm
x
A

FIG. 2

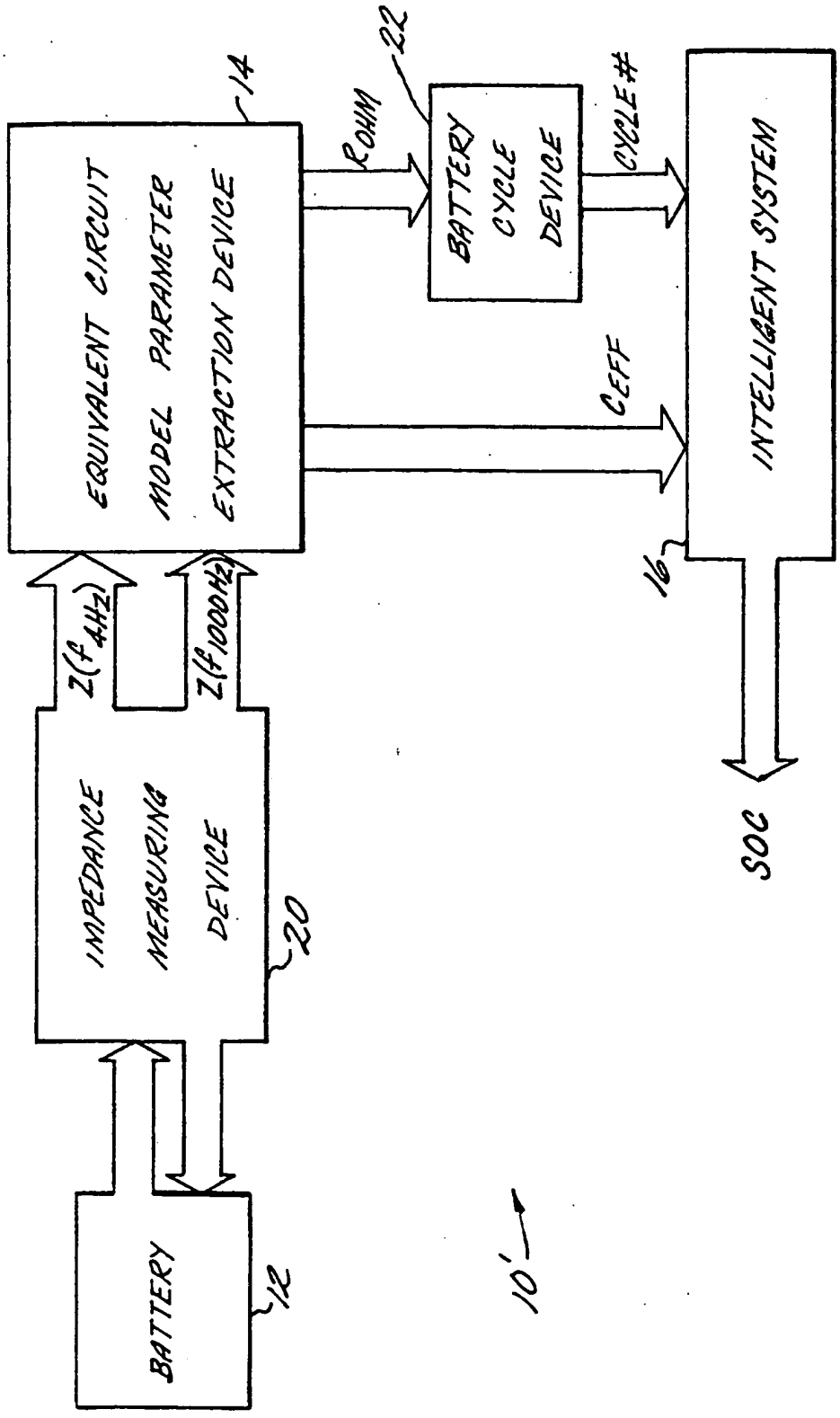

BATTERY
12
IMPEDANCE MEASURING DEVICE
20
Z(f 442)
Z(f 1000Hz)
EQUIVALENT CIRCUIT MODEL PARAMETER EXTRACTION DEVICE
14
ROHM
22
BATTERY CYCLE DEVICE
CYCLE #
CEFF
INTELLIGENT SYSTEM
16
SOC
10'

FIG. 3

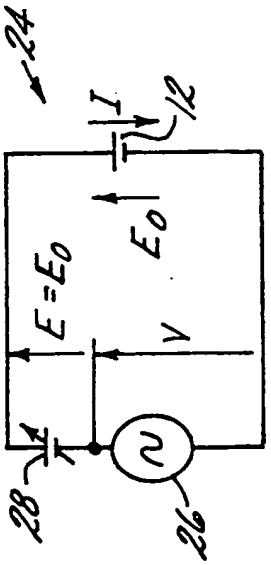


FIG. 4A

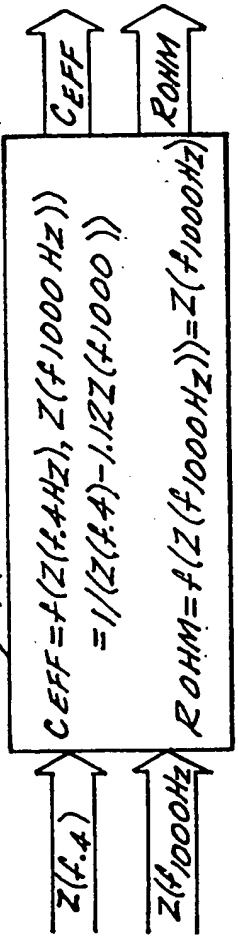


FIG. 4B

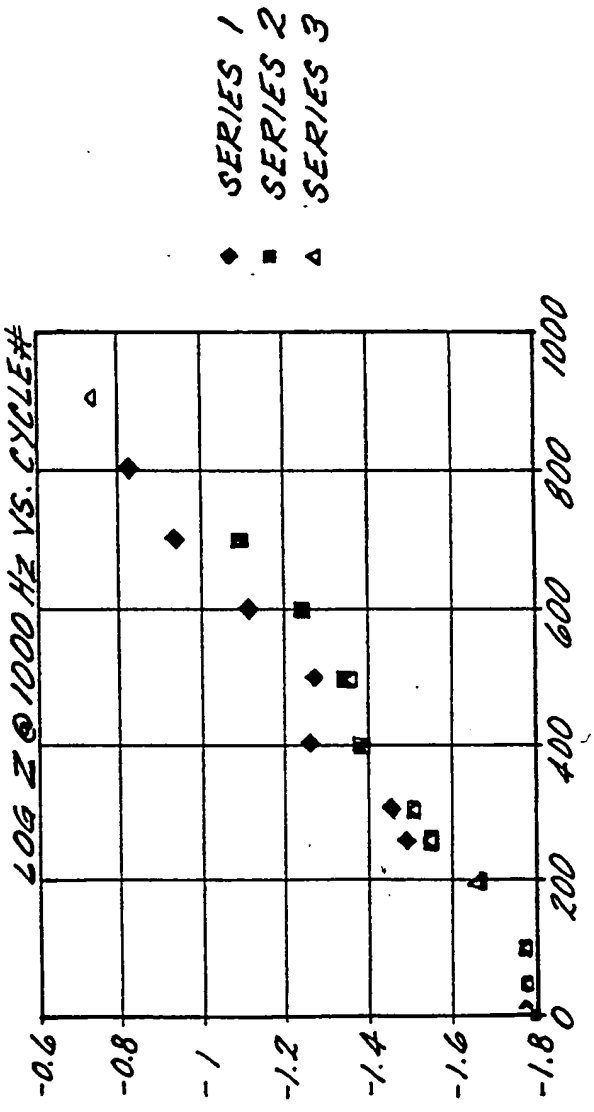


FIG. 4C

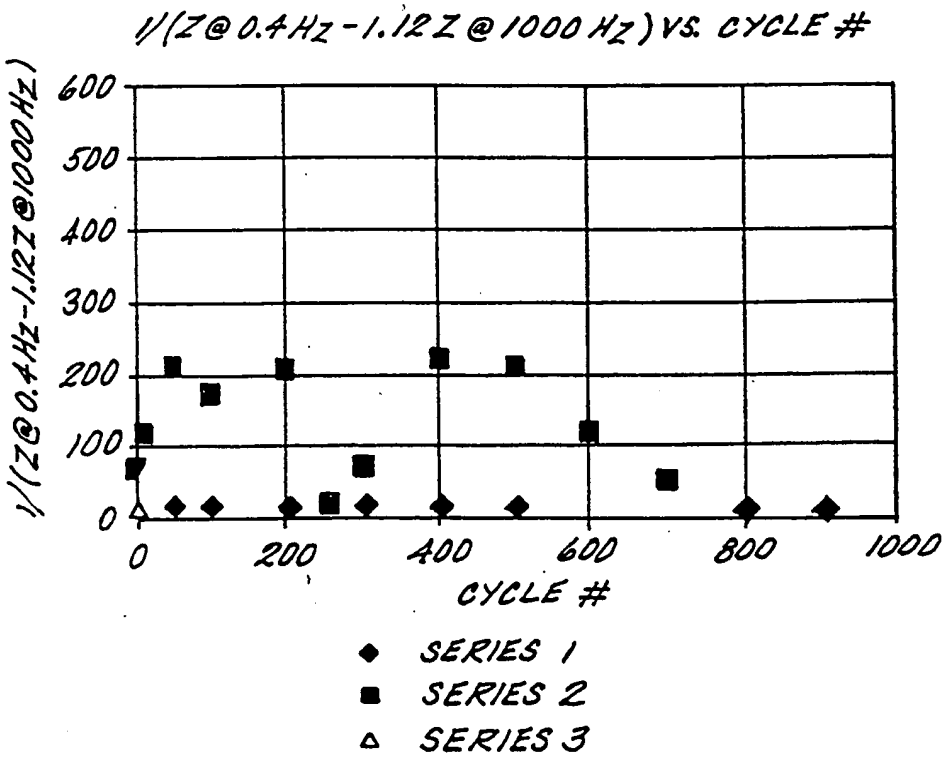

1/(Z@0.4Hz-1.12Z@1000Hz) VS. CYCLE #
1/(Z@0.4Hz-1.12Z@1000Hz)
600
500
400
300
200
100
0
0
200
400
600
800
1000
CYCLE #
SERIES 1
SERIES 2
SERIES 3

FIG. 5

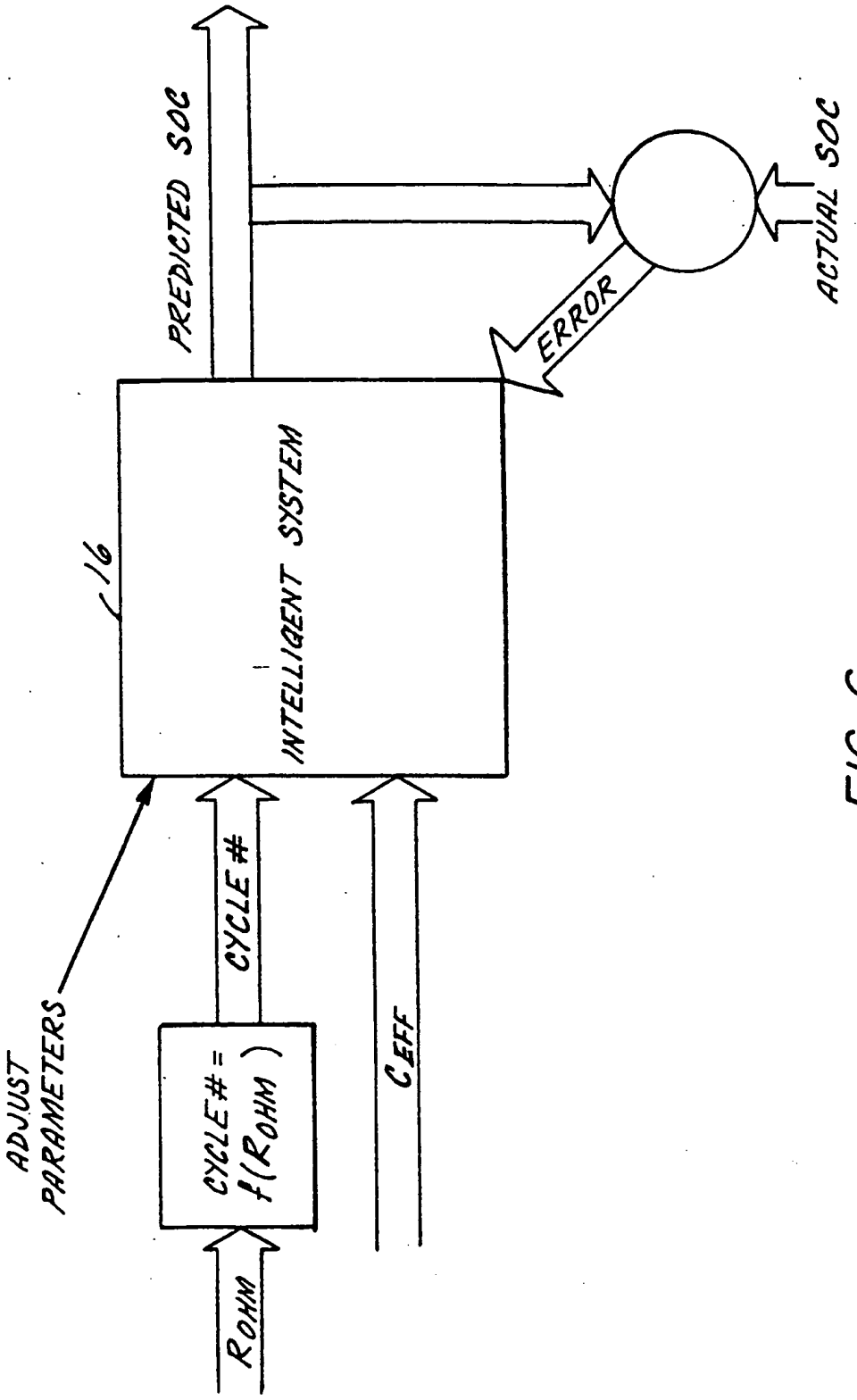

PREDICTED SOC
ACTUAL SOC
ERROR
INTELLIGENT SYSTEM
16
ADJUST PARAMETERS
CYCLE #
CYCLE# = f(ROHM)
CEFF
ROHM

FIG. 6

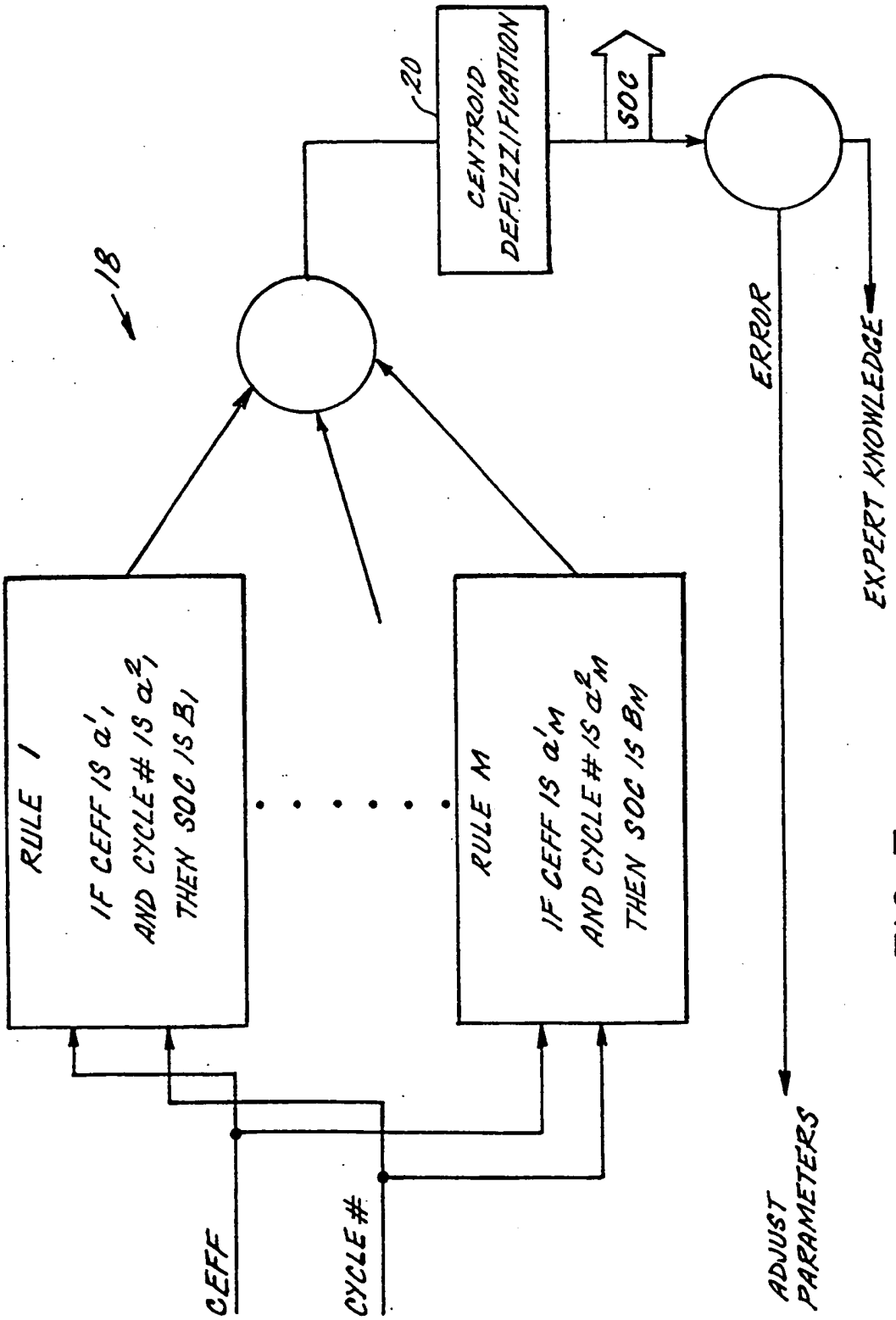

18
20
CENTROID DEFUZZIFICATION
SOC
ERROR
EXPERT KNOWLEDGE
RULE 1
IF CEFF IS a^1_1
AND CYCLE # IS a^2_1
THEN SOC IS B_1
RULE M
IF CEFF IS a^1_M
AND CYCLE # IS a^2_M
THEN SOC IS B_M
CEFF
CYCLE #
ADJUST PARAMETERS

FIG. 7

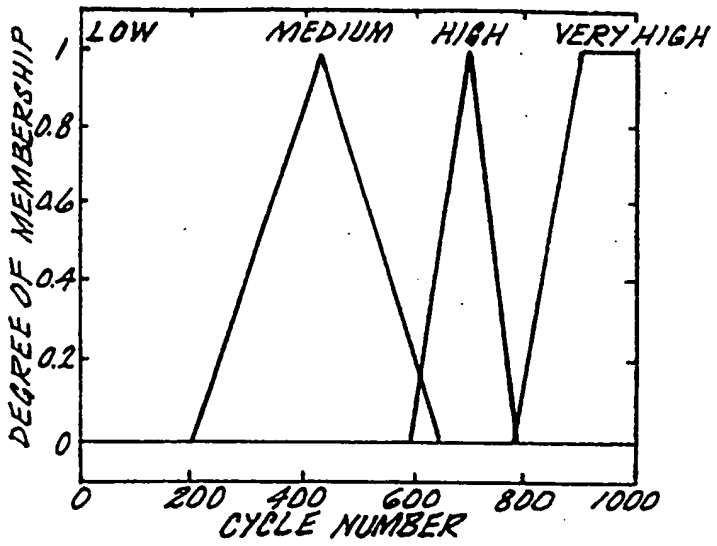


FIG. 8A

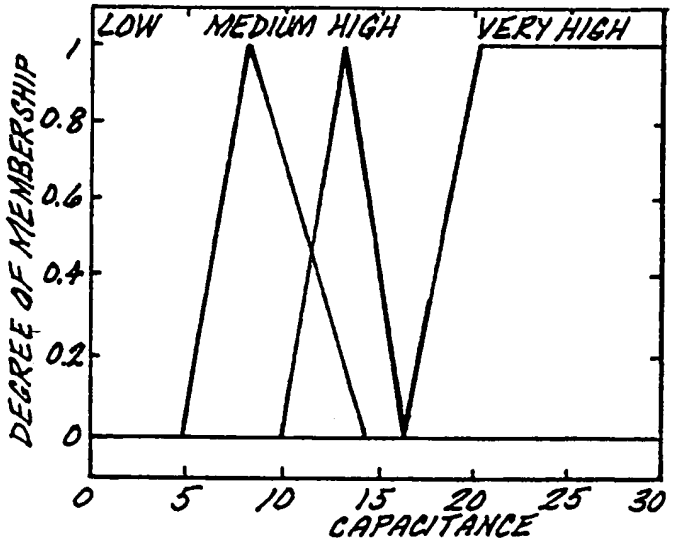


FIG. 8B

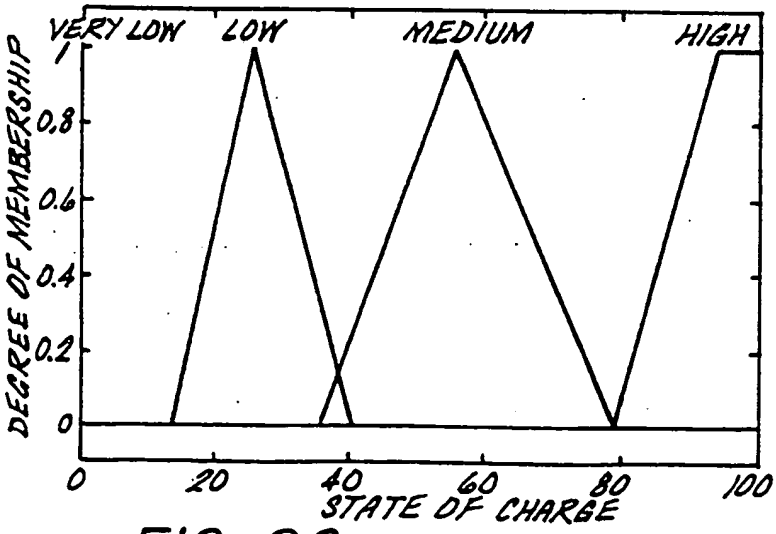


FIG. 8C

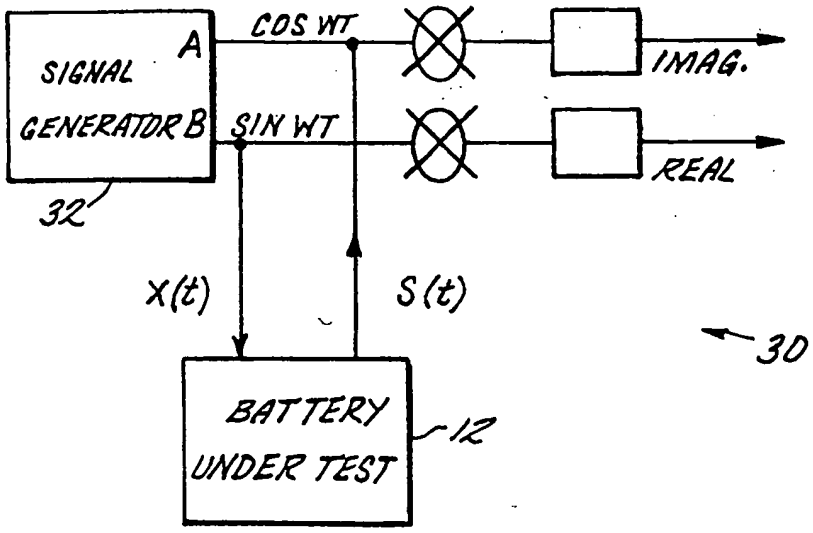

SIGNAL GENERATOR
A
B
COS WT
SIN WT
IMAG.
REAL
32
X(t)
S(t)
30
BATTERY UNDER TEST
12

FIG. 9A

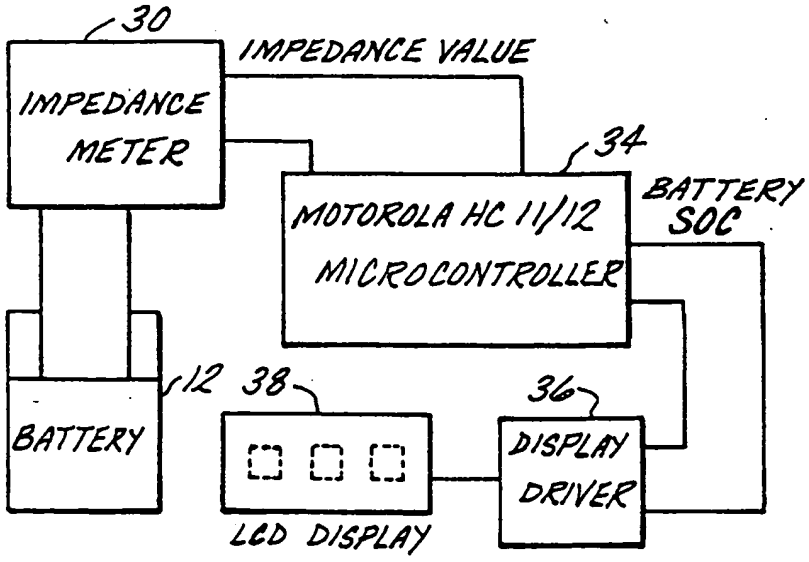

30
IMPEDANCE METER
IMPEDANCE VALUE
34
MOTOROLA HC 11/12 MICROCONTROLLER
BATTERY SOC
12
BATTERY
38
LCD DISPLAY
36
DISPLAY DRIVER

FIG. 9B

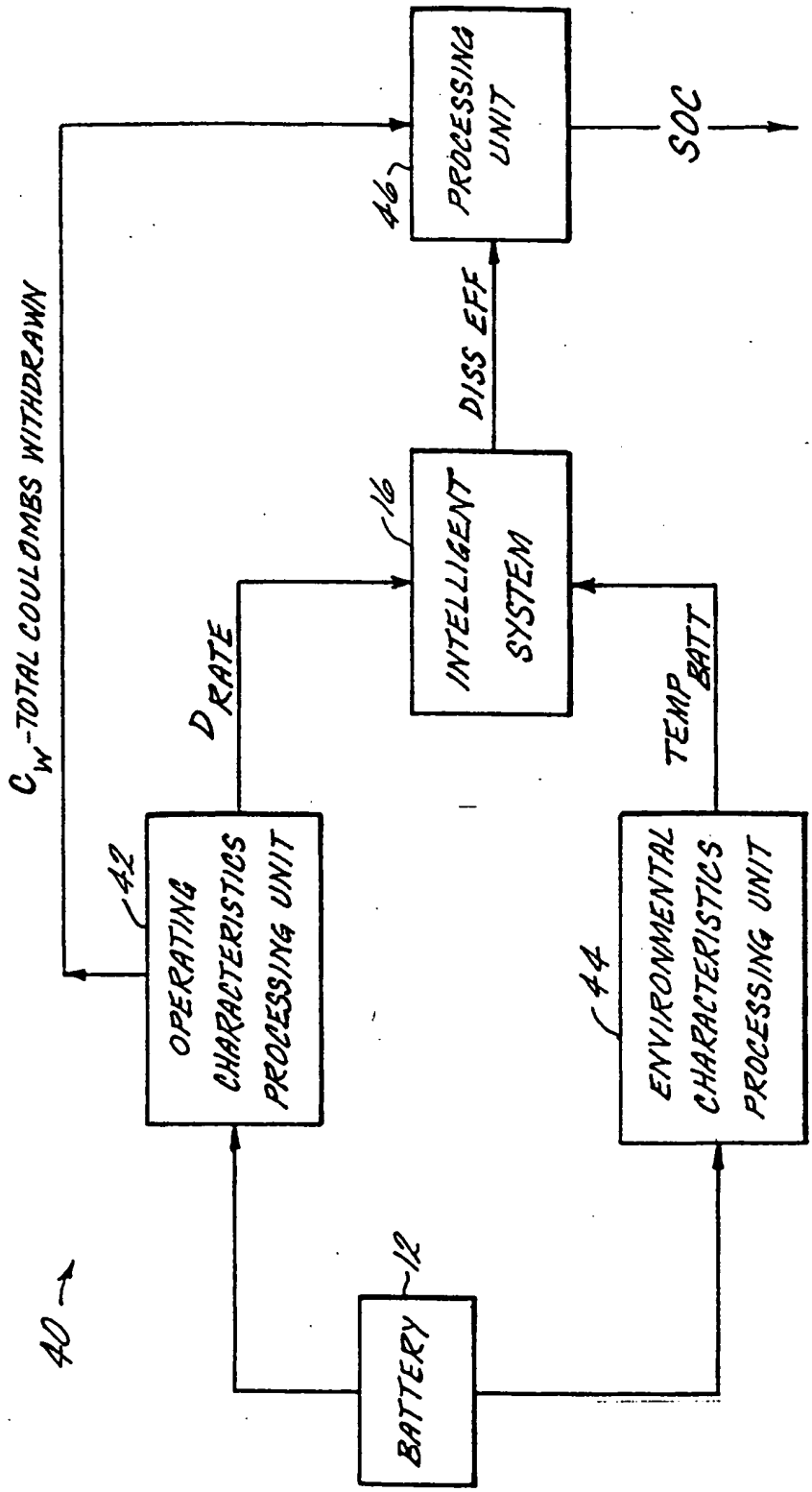

40
BATTERY
12
OPERATING CHARACTERISTICS PROCESSING UNIT
42
ENVIRONMENTAL CHARACTERISTICS PROCESSING UNIT
44
INTELLIGENT SYSTEM
16
PROCESSING UNIT
46
SOC
C_W - TOTAL COULOMBS WITHDRAWN
D_{RATE}
DISS EFF
$TEMP_{BATT}$

FIG. 10

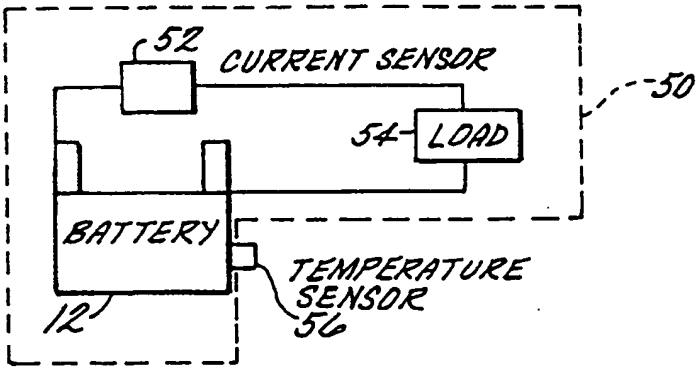


FIG. 11A

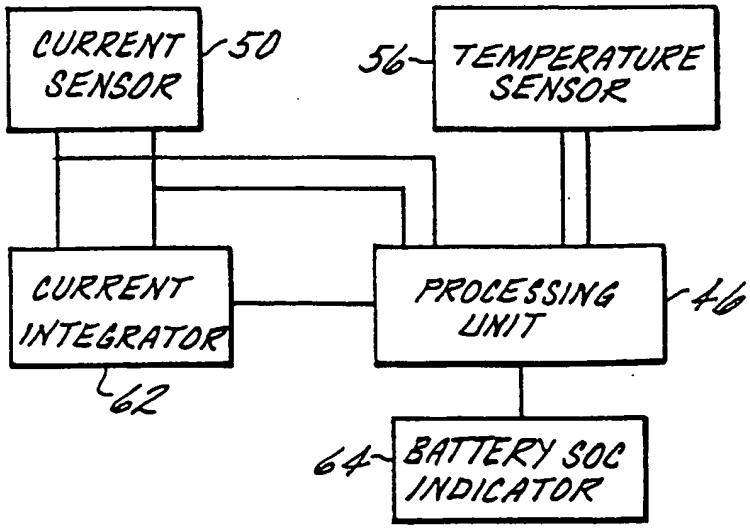


FIG. 11B

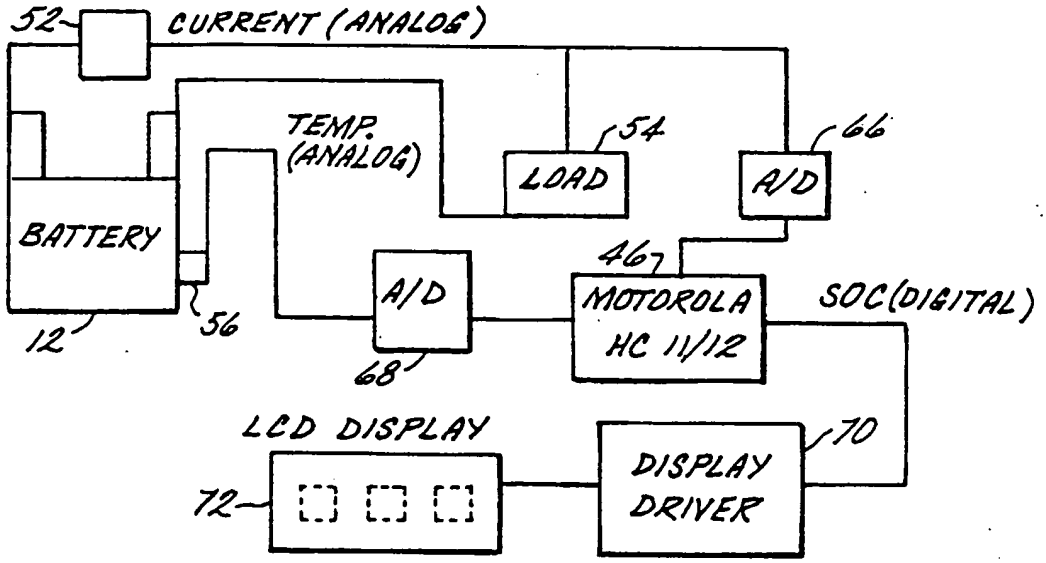


FIG. 11C

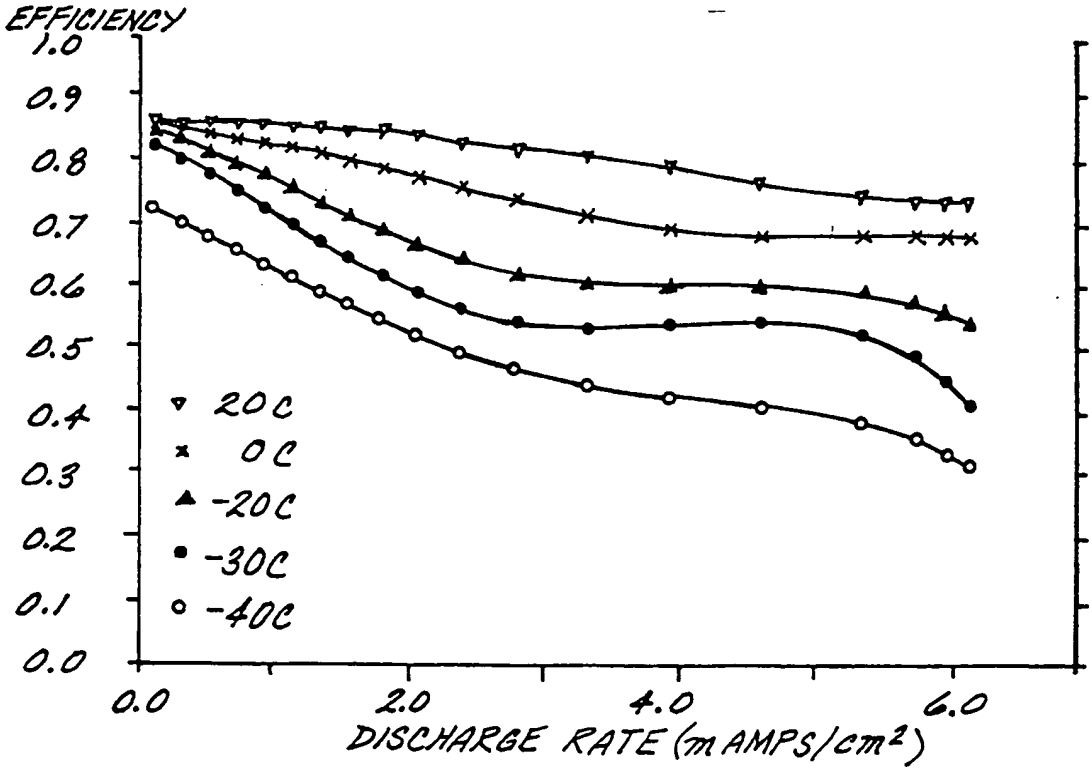


FIG. 12

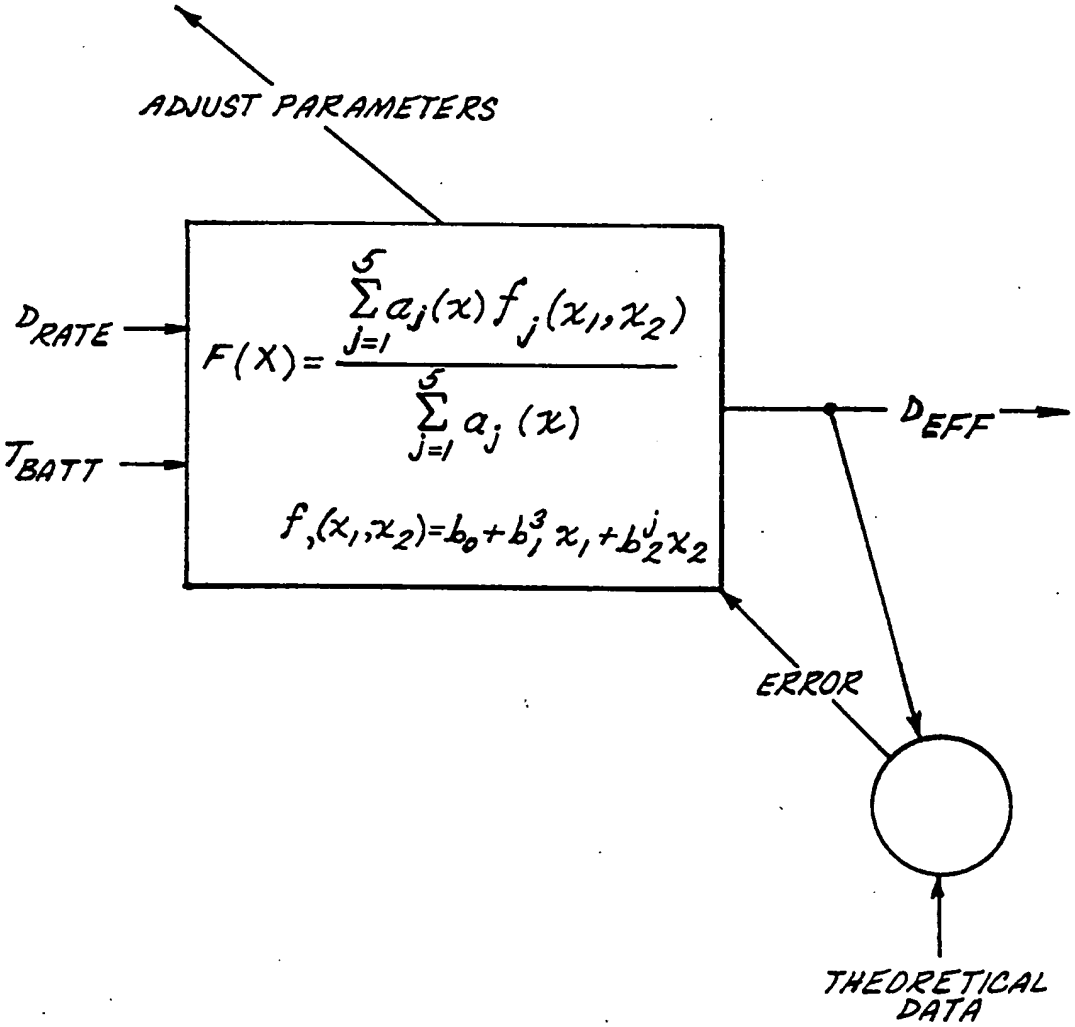

ADJUST PARAMETERS
D_{RATE}
T_{BATT}
$F(X)=\frac{\sum_{j=1}^{5} a_j(x) f_j(x_1,x_2)}{\sum_{j=1}^{5} a_j(x)}$
$f_j(x_1,x_2)=b_0+b_1^3 x_1+b_2^j x_2$
D_{EFF}
ERROR
THEORETICAL DATA

FIG. 13

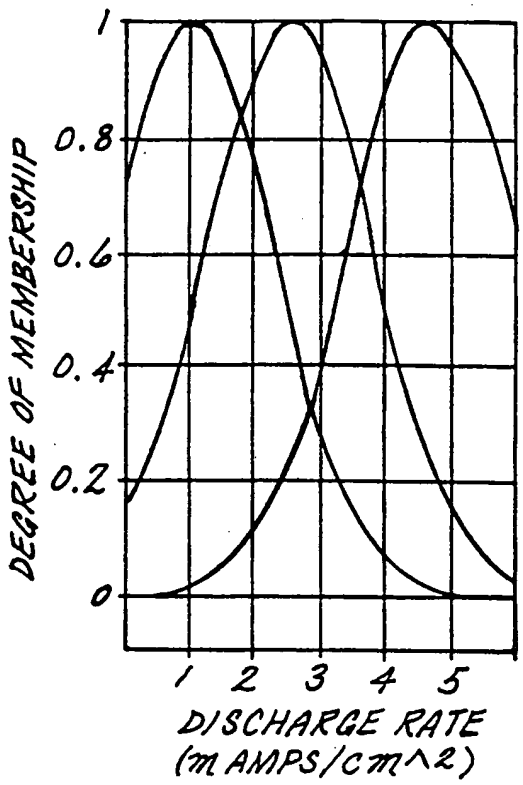


FIG. 14A

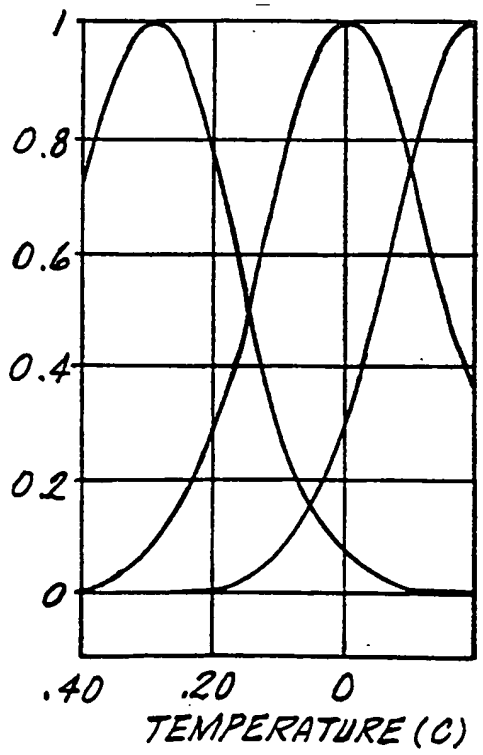


FIG. 14B

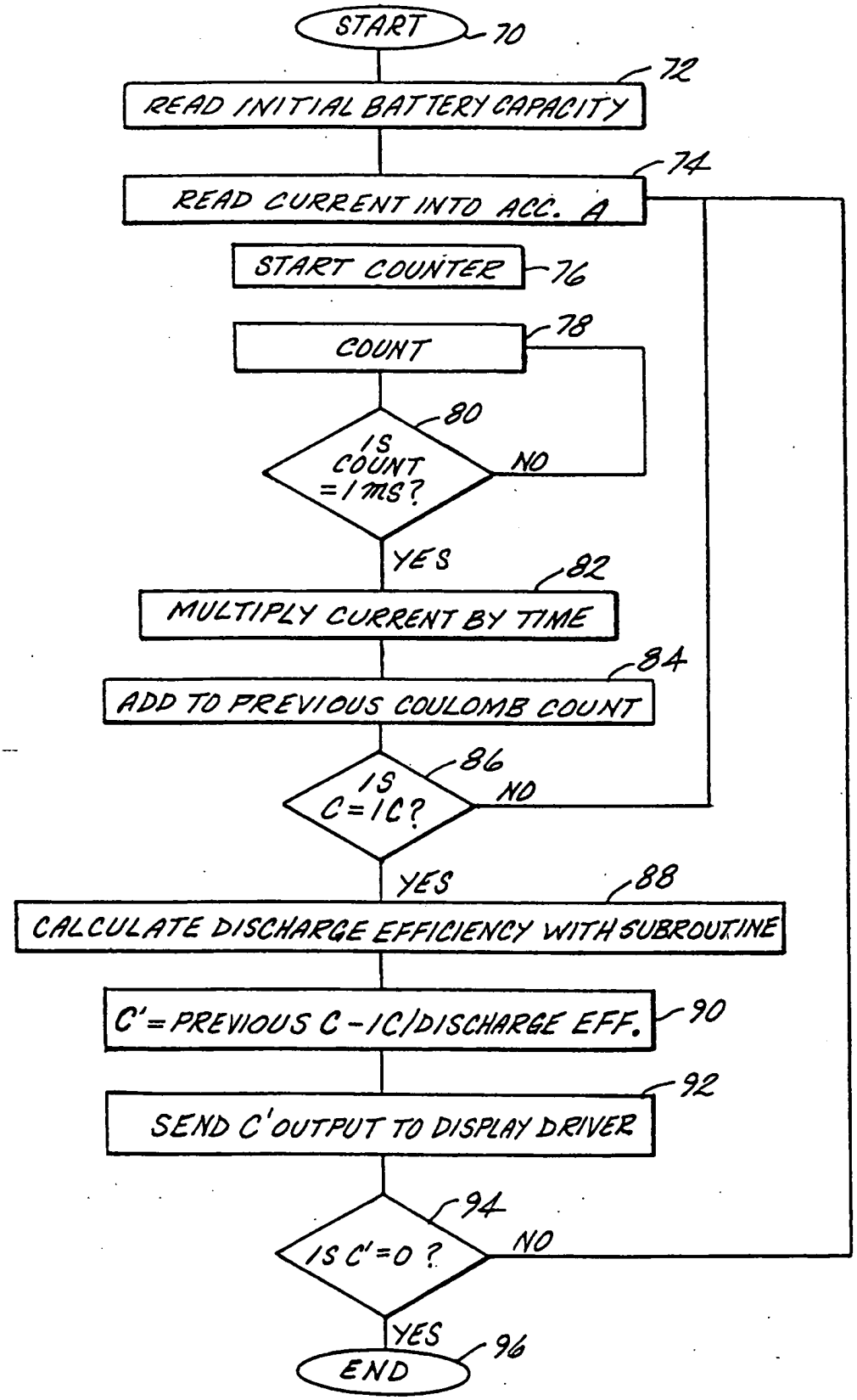

START
70
READ INITIAL BATTERY CAPACITY
72
READ CURRENT INTO ACC. A
74
START COUNTER
76
COUNT
78
IS COUNT =1 ms?
80
NO
YES
MULTIPLY CURRENT BY TIME
82
ADD TO PREVIOUS COULOMB COUNT
84
IS C=IC?
86
NO
YES
CALCULATE DISCHARGE EFFICIENCY WITH SUBROUTINE
88
C'=PREVIOUS C-IC/DISCHARGE EFF.
90
SEND C' OUTPUT TO DISPLAY DRIVER
92
IS C'=0 ?
94
NO
YES
END
96

FIG. 15

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US98/04883

A. CLASSIFICATION OF SUBJECT MATTER
IPC(6) :H01M 10/46
US CL :320/137
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 320/132, 134, 136, 137, 149, 150, 160, 161 and 162.

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	LIANG, Y.C. Design of Battery Charging System with Fuzzy Logic Controller. International Journal of Electronics. July 1993. vol 75, no. 1	1-33
Y	McCARTY, D. Using a Fuzzy Logic Controller for Intelligent Battery Charging. Conference Proceedings of High Freq Power Conversion. April 1994. pp 242-255	1-33
Y	GERALD, O. Adaptive System for Smart Battery Management based on Neural Networks. Stage effectue aux Laboratoires d'Electronique Phillips. September 1995. pp 1-24.	1-33

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search
03 AUGUST 1998

Date of mailing of the international search report
24 AUG 1998

Name and mailing address of the ISA/US
Commissioner of Patents and Trademarks
Box PCT
Washington, D.C. 20231
Facsimile No. 703.305.3230

Authorized officer
PETER S WONG
Telephone No. 703.305.3477

Form PCT/ISA/210 (second sheet)(July 1992)*